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Design and Analysis of a Prototype Range Correction Device for a Mortar Projectile

Michael S.L. Hollis

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Design and Analysis of a Prototype Range Correction Device for a Mortar Projectile

Michael S.L. Hollis
Weapons and Materials Research Directorate

Abstract

The primary purpose of the Light Forces Program is to improve the effectiveness of indirect fire from the infantry mortar without increasing the logistics burden on the soldier. Technology will enable improvements in mortar launcher design, aiming, meterological data, and projectile design. Advances in microelectronics, sensors, and power supplies make it possible to design and build a miniature, one-dimensional range-correction device for the mortar. The objective of a range correction device is to provide a smart munition capability of reducing range error, thus increasing the lethality. Another objective is to place the device between the existing fuze and mortar projectile without impinging on the fuze function and the aerodynamics of the projectile. The device must also be miniature to reduce the impact in logistics or cost.

A more definitive explanation of the range correction idea for a mortar is as follows. The device is assembled onto the projectile while in the field. An on-board central processing unit (CPU) is preprogramed with the target location and the firing location coordinates. The mortar is then aimed to fire beyond the target location. An on-board inertial measurement unit (IMU) determines the range error with respect to the target while the projectile is in flight. The CPU predicts the amount of excessive range that the mortar will have. At a certain time in flight, chosen by the CPU, the range correction device deploys eight small, flat, planar surfaces or flare tabs. The effect is to create more drag on the projectile to correct for the "over-shoot," thus reducing the range error aspect of the flight. This report focuses on one specific range correction concept and the progress of the design; it also covers the mechanical design of the flare tab mechanisms, the electronics volume, and the structural analysis of the overall design.

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DESIGN AND ANALYSIS OF A PROTOTYPE RANGE CORRECTION DEVICE FOR A MORTAR PROJECTILE

1. INTRODUCTION

The primary purpose of the Light Forces Program is to improve the effectiveness of indirect fire from the infantry mortar without increasing the logistics burden on the soldier. Technology will enable improvements in mortar launcher design, aiming, meteorological data, and projectile design. Advances in microelectronics, sensors, and power supplies make it possible to design and build a miniature, one-dimensional, range correction device for the mortar. The Advanced Munitions Concepts Branch (AMCB) of the Ballistics and Weapons Concepts Division (BWCD), Weapons and Materials Research Directorate of the U.S. Army Research Laboratory (ARL), has been doing design work in the area of self-correction devices for artillery since 1996. Recent reports such as "Low Cost Competent Munitions (LCCM) Self-Correction Devices - An Initial Study and Status" and "Preliminary Design of a Range Correction Module for an Artillery Shell" demonstrate the branch's interest in improving the ballistic accuracy of artillery projectiles (D'Amico 1996; Hollis 1996).

Figure 1 shows a simplified error "budget" for a fin-stabilized ballistic projectile. The oval represents the impact area of the projectile. Range error is depicted by the length of the oval, whereas the width symbolizes the error attributable to deflection. The objective of a range correction device is to provide a smart munition capability of reducing range error, thus increasing the lethality. Another objective is to place the device between the existing fuze and mortar projectile without impinging on the fuze function and the aerodynamics of the projectile. The device must also be miniature to reduce the impact in logistics or cost.

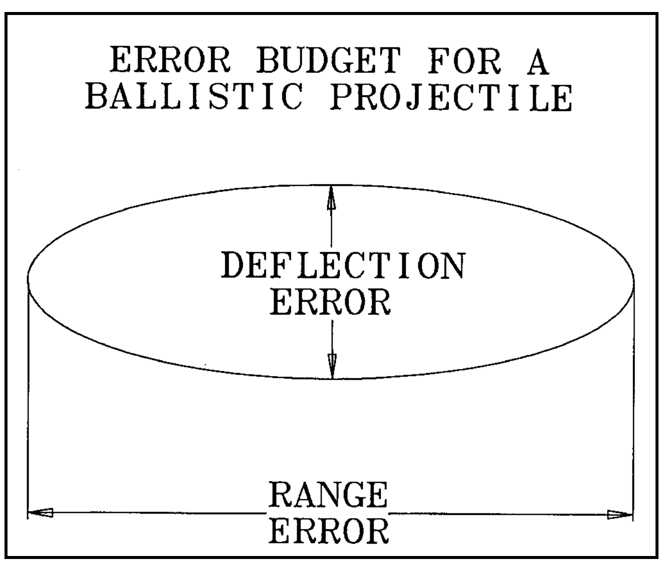

Figure 1. Error "Budget" for a Ballistic Projectile.

Since the device is located between the fuze and the projectile body of the mortar, the fuze is extended by a few centimeters. The cylindrically shaped body of the device will minimally affect the aerodynamics of the mortar during free flight. Figure 2 depicts a model of an 81-mm, M821 mortar with a point-detonating M525 fuze. Figure 3 displays the same mortar with the range correction device.

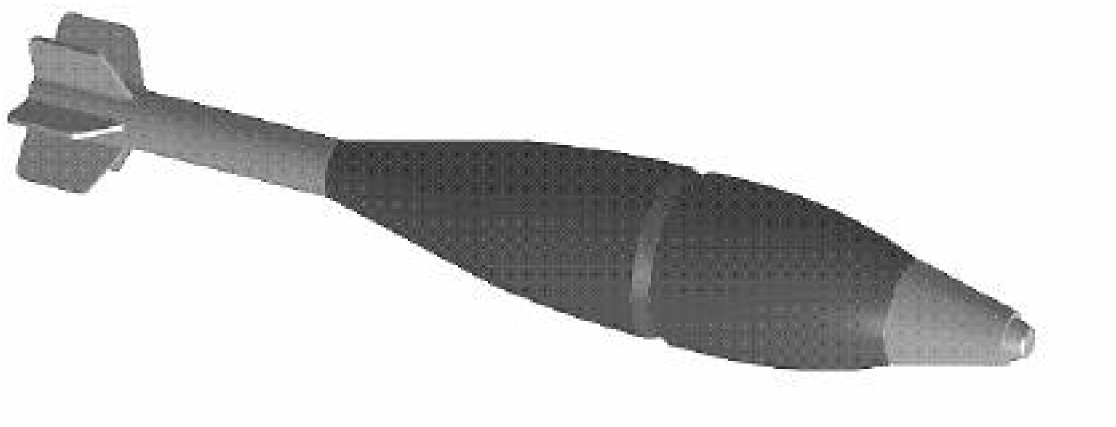

Figure 2. An M821 Mortar With a Standard Point-Detonating M525 Fuze.

Figure 3. An M821 Mortar With a Range Correction Device Installed.

The booster cup, which normally screws into the fuze, now screws into the device opposite the fuze. A small hollow tube runs down the center of the device. This tube allows the ignition flame from the fuze to travel down the tube and ignite the charge in the booster cup. Enhancement of this process may be necessary, but it is unknown at this time. Figure 4 contains a detailed view of the range correction device in the deployed configuration.

Figure 4 depicts the deployed small flat planar surfaces or flare tabs. The effect is to create more drag on the projectile. A more definitive explanation of the range correction idea for a mortar is as follows. The device is assembled onto the projectile while in the field. An on-board central processing unit (CPU) is preprogrammed with the target location and the firing location coordinates. The mortar is then aimed to fire beyond the target location. An on-board inertial measurement unit (IMU) will determine the range error with respect to the target while the projectile is in flight. The CPU predicts the amount of excessive range that the mortar will have. At a time in flight, chosen by the CPU, the flare tabs will deploy to correct for the "over-shoot," thus reducing the range error aspect of the flight. This report focuses on one specific range correction concept and the progress of the design; it also covers the mechanical design of the flare tab mechanisms, the electronics volume, and the structural analysis of the overall design.

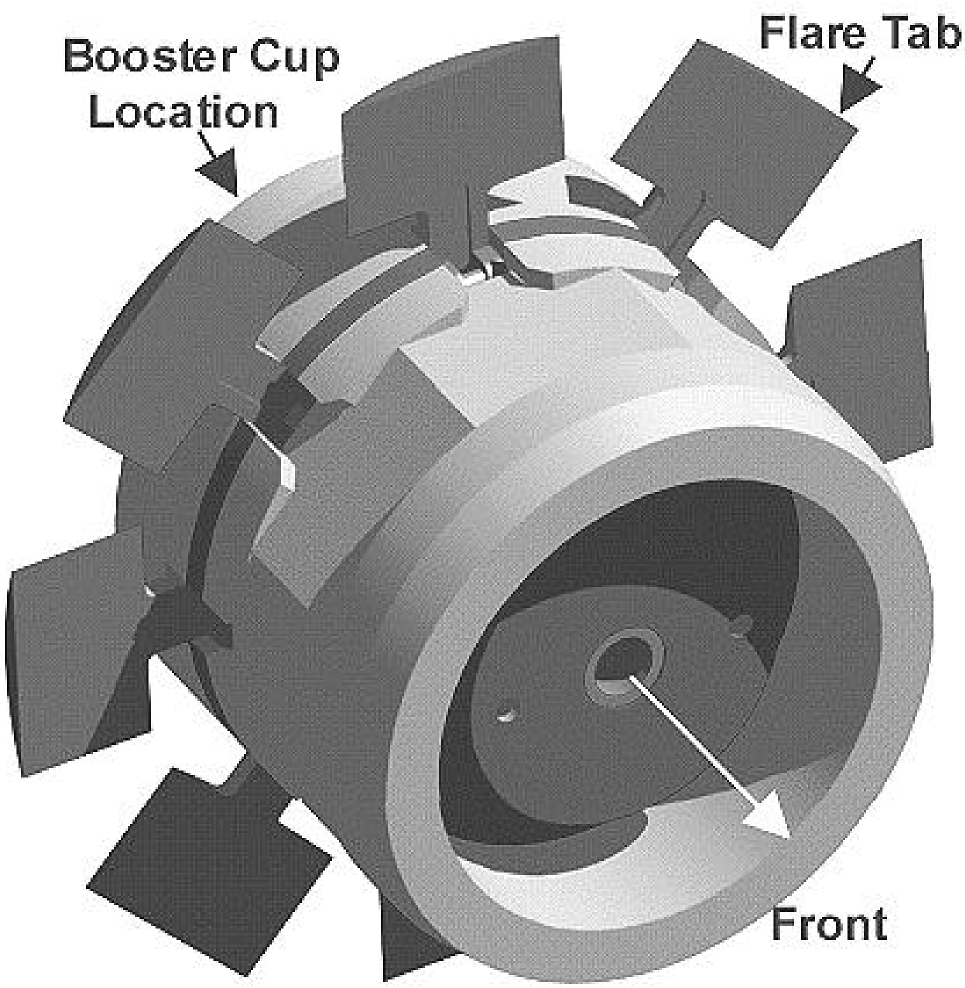

Figure 4. Detailed View of the Deployed Range Correction Device.

2. MECHANICAL DESIGN

The gun-launch prototype mechanical design consists of many parts, several of which are spring loaded and moving in concert. Figure 5 displays an exploded view of the prototype design. The module base and the module front have external and internal threads, respectively. This allows for easy installation into the mortar body since the module base has the same threads as a standard mortar-type fuze. In addition, the module base also has internal threads to fit the booster charge that normally screws into the fuze. A standard fuze, such as the M525, can then thread into the module front. The assembled device extends the fuze from the body by 1.6 inches (40.6 mm).

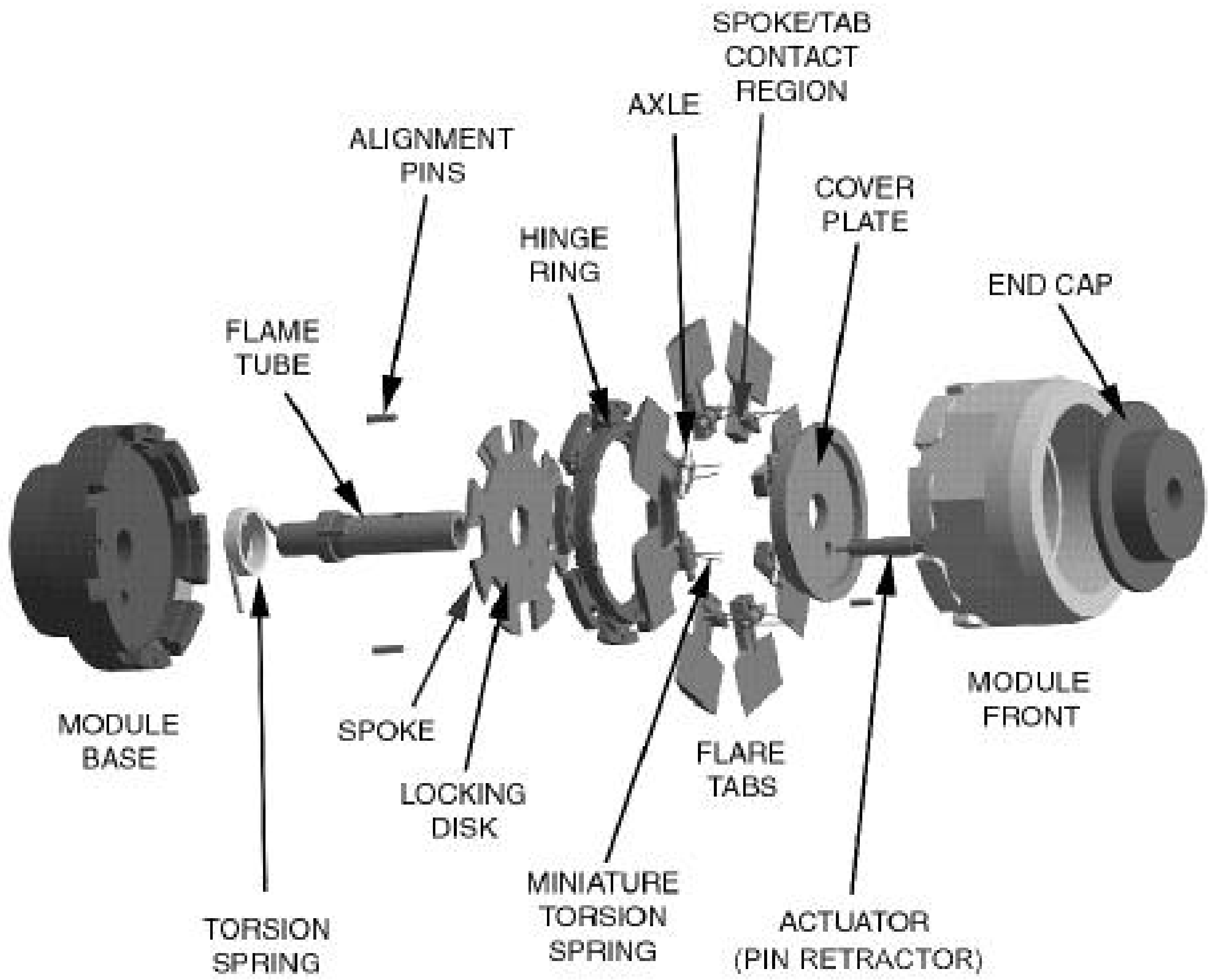

Figure 5. The Exploded Assembly View of the Prototype Range Correction Device for a Mortar.

The device must hold electronics and a release mechanism. Simultaneously, a means to allow the fuze to ignite the booster charge must exist, since the two are now separated. As one can see from Figure 5, the device contains two adjacent compartments separated by the cover plate. One compartment contains electronics and the other the release mechanism. The flame tube provides the means so that the fuze can ignite the booster charge. This simple hollow tube also provides the means that holds the entire device together. During a launch, the stacking approach used to assemble the device carries the set-back loads. Alignment pins help in the proper positioning of the module base, the hinge ring, and the module front. The flame tube is crucial during the rebound loads and the balloting loads of the launch. The flame tube is threaded on both ends so that the one end threads into the module base whereas the end cap threads onto the flame tube. As the end cap turns about the flame tube, it clamps the entire assembly together. Stress analyses done on the assembly are discussed later in this report.

The volume created for electronics in this prototype is 1 inch^3 (16.4 mm^3). This is extremely small for electronics and a power supply. This prototype, however, is not a final solution. Smaller mechanisms exist so that they could allot more room to the electronics. The electronics, such as an IMU, a CPU, and power supply are constantly being reduced in size with advances in technology. The Hardened Subminiature Telemetry and Sensor System (HSTSS) program can telemeter spin data in real time from a kinetic energy projectile. That program used the same amount of volume previously mentioned. Such miniaturized and ruggedized electronics could possibly be used to decide when the range correction device should deploy the flare tabs.

When deployed, eight flare tabs provide the actual means of range correction by creating an increase in drag. The flare tabs are originally locked in place, flush with the module front, as seen in Figure 3. In this position, the tabs create a cylindrical surface that will have the least effect on the aerodynamics of the projectile. The flare tabs are locked by means of an internal locking disk, as seen in Figure 5. The spokes of the locking disk push on the underside of the flare tabs. The locking disk is pre-loaded via a torsion spring. The pin of the pin retractor actuator, which is an electro-explosive device, maintains the locking disk in the pre-loaded or locked position. At the desired time in flight, the pin retractor actuator will retract its pin, freeing the locking disk and allowing it to rotate. The flare tabs, which are also individually spring loaded, will rotate through the slots in the locking disk. As the flare tabs pivot to the deployed 90°, the spokes of the locking disk, which are beveled, slide under the flare tabs. This locks the tabs in the deployed position. The timing of this sequence is critical. By the use of video monitoring and trial and error, the timing of the overall mechanisms was adjusted to allow for the proper functioning of the device.

3. STRUCTURAL ANALYSIS

3.1 Introduction

A series of linear, static, three-dimensional, finite element analyses was performed on the assembly. This included the module base, the hinge ring, the module front, the flame tube, and the end cap. The software used to create models and solve them was Structural Dynamics Research Corporation's (SDRC) Integrated Design, Engineering, and Analysis Software (I-DEAS). The final analysis was verified with shock tests that were accomplished using an IMPAC shock table. A dynamic analysis was conducted to determine the loading on the flare tab attributable to deployment while in flight. A detailed discussion of the dynamic analysis is given in Condon (1998).

3.2 Assumptions

The objective for conducting finite element analyses on the assembly was to ascertain the viability of the design subjected to set-back and balloting loads that occur during the launch. Since the geometry is not two-dimensional axisymmetric, the model was created in three dimensions. However, the geometry has symmetry in the sense that eight flare tabs exist. The eight flare tabs required eight equal sections that could be divided again into 16 equal parts. Figure 6 depicts the geometry that was used for the analysis. This symmetrical condition, which was used to expedite the analyses and to reduce the model file size, was simulated by using circumferential restraints on the sides of the geometry. Also seen in the figure are the vectors for the set-back and balloting load cases. Neither the internal electrical components nor the electrical potting epoxy were modeled.

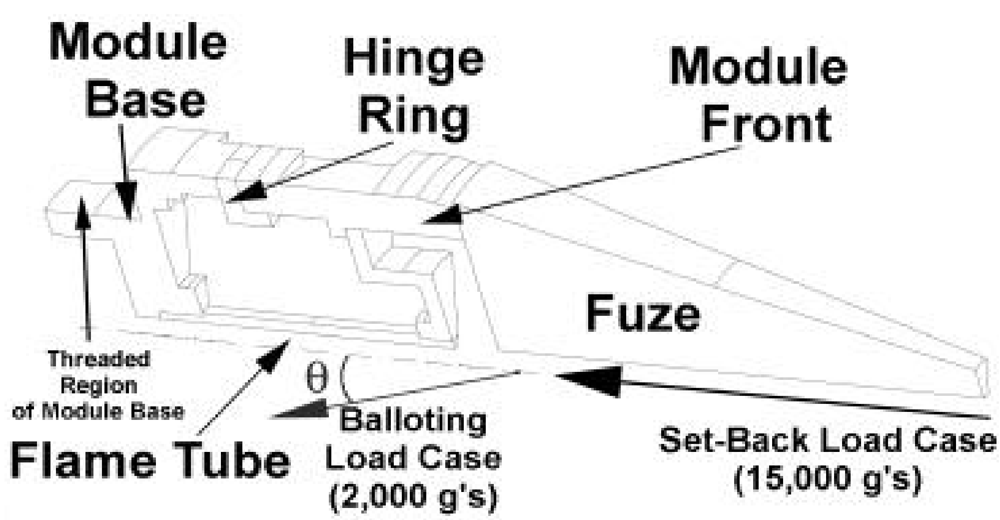

Figure 6. The Geometry Used to Perform the Finite Element Analyses.

The set-back load case contained an acceleration vector with a magnitude of 15,000 g's. The balloting load case involved an acceleration vector with a magnitude of 2,000 g's and an angle from the symmetry axis of 11.25°. Restraining the threaded region of the module base grounded the model for both load cases in all three translational degrees of freedom.

3.3 Model Construction

The geometry in Figure 6 was approximated with 4,240 solid, parabolic, tetrahedral elements and 364 linear gap elements. The gap elements were mostly used to emulate contact between parts in the axial direction. Several gap elements were also used to model radial contact between various parts. The threads of the flame tube were not modeled to simplify modeling. Instead, the diameter of the geometry equaled the pitch diameter of the threads. The nodes of the threaded interface regions were merged to constrain the parts.

Figure 7 displays the finite element model. Table 1 lists the materials used for the various parts of the model. Since the structural response of the fuze was not in question, the fuze region was modeled as a lumped mass which simulated the extra loads because of the fuze. The flame tube has a highly refined discretization to resolve any high stresses that might have occurred.

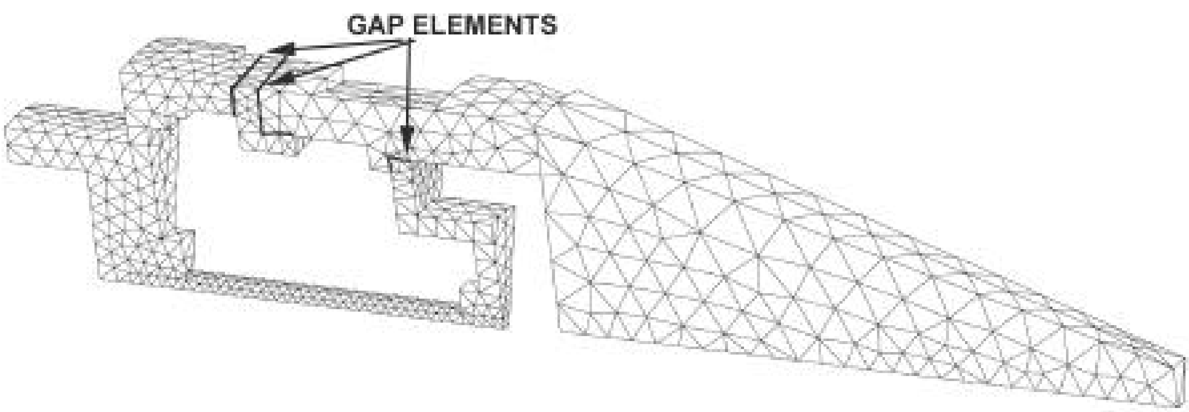

Figure 7. The Finite Element Model Used for the Numerical Analysis.

Table 1

Material Properties

Part	Material	Density (lb/in^3)/[g/cc]	Yield Strength ksi (MPa)
Fuze	modified density	(.133)/[3.69]	N/A
Module Front	Al 7075-T651	(.101)/[2.79]	73 (503)
Hinge Ring	Al 7075-T651	(.101)/[2.79]	73 (503)
End Cap	Steel	(.283)/[7.83]	142 (980) min
Module Base	Al 7075-T651	(.283)/[7.83]	73 (503)
Flame Tube	Steel	(.283)/[7.83]	142 (980) min

4. STRESS ANALYSIS

4.1 Von Mises Stress Criteria

The von Mises stress criterion is a theory that specifies that plastic yielding will occur when the combined stresses of a body equal or exceed the tensile yield stress of a metal. The von Mises stress failure criterion has been validated by previous empirical studies (Sorenson 1992). Von Mises, σ', is represented by the following equation:

$$\sigma' = \left\{ \frac{\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2\right]}{2} \right\}^{1/2}$$

in which σ_1, σ_2, and σ_3 are the principal stresses and

$$\sigma_1 > \sigma_2 > \sigma_3$$

Plastic yielding is predicted to occur when the von Mises stress is $\geq$ the yield stress, σ_{yield}, of the material. If the design has extensive areas of plastic yielding, then it is likely to suffer unacceptable deformations and possibly even fracture in service. However, if only small localized regions of yielding are predicted, then it is presumed that some redistribution of material through plastic flow will alleviate these high stress areas.

4.2 Results

The predicted von Mises stresses, attributable to the applied set-back load of the first load case, are well within the yield strengths of the specified materials. As one can see from Figure 8, the maximum magnitude of stress was approximately 50 Ksi (345 MPa). Black represents the

lower end of the resulting stresses, whereas the light gray represents higher magnitude of stress. Figure 9 displays the von Mises stress contour plot for the second case. The second load case represents a possible balloting load that occurs during a launch. As one can see, the stresses attributable to this load are insignificant compared with the yield strengths of the materials involved in the design.

5. CONCLUSIONS

The stress analyses show that the stresses are well below the yield strengths of the materials in the design. In addition, a prototype device was fabricated and repeatedly shocked on an IMPAC shock table. The average magnitude of the shocks was about 14,000 g's with a duration of 0.0001 second. This shock pulse is an order of magnitude shorter than that from a gun launch. However, experience with the IMPAC shock table has shown that if a device can survive the short pulse, then it stands a very good chance of surviving a gun launch shock pulse of the same magnitude. Therefore, the fact that the device survived several shocks verifies the analysis of the set-back load case. Based on these results, the design could be further optimized to accommodate more volume for electronics. Further improvements in miniature mechanism design could also improve the electronics volume capacity. Considering the available technologies and volume constraints, it appears that the range correction module, with a single deployment scheme, is a distinct possibility. Some aggressive technologies, such as power supplies and sensors, could be leveraged from HSTSS technologies.

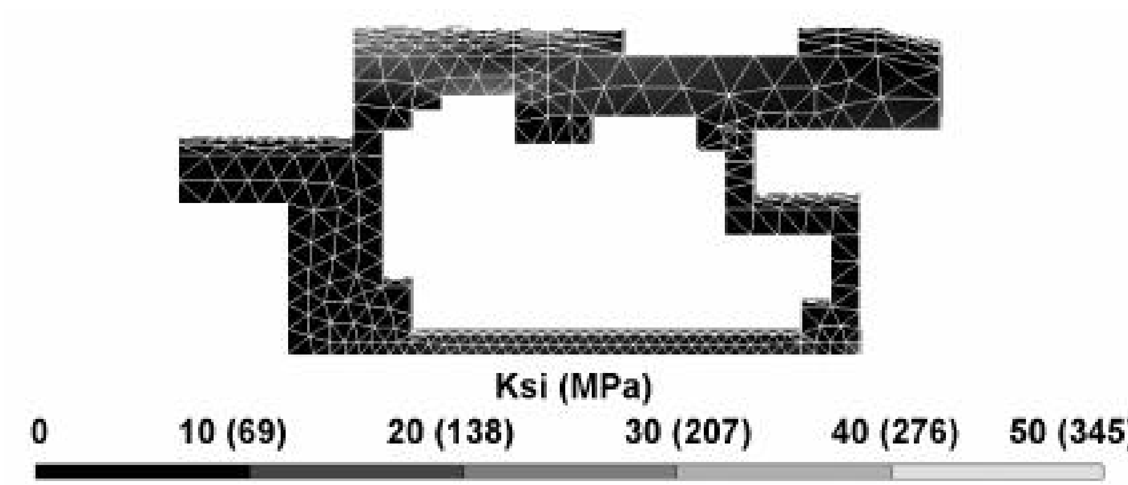

Figure 8. Von Mises Stress Results Attributable to 15,000 g's of Set-Back Acceleration.

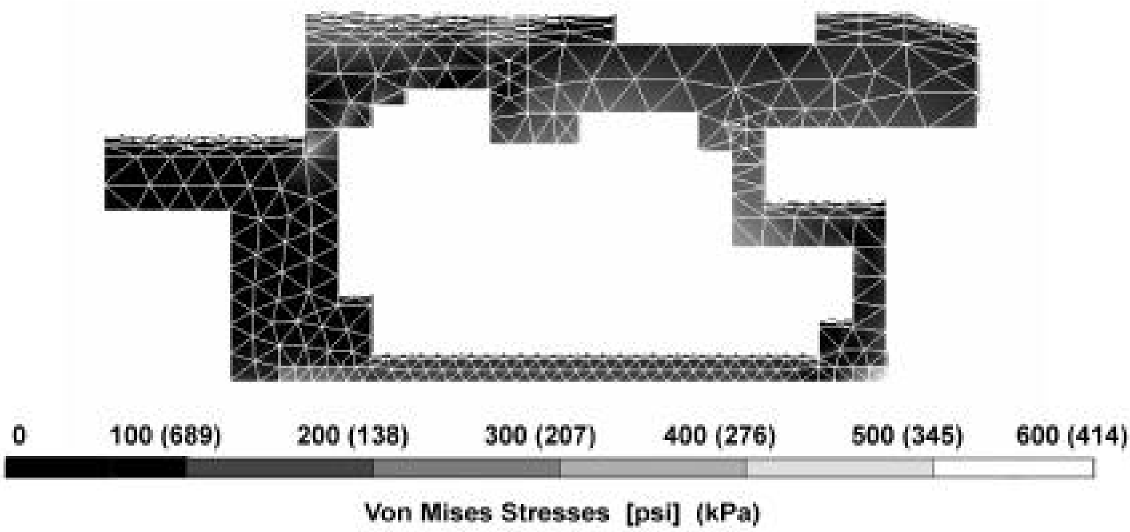

Figure 9. The von Mises Stresses for the Balloting Load Case.

To determine the overall effect the design would have on the trajectory of a mortar projectile, it is recommended that a prototype device be flight tested. The device should contain off-the-shelf electrical components to produce a simple timing and firing circuit to deploy the flare tabs while the projectile is in flight.

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13. ABSTRACT *(Maximum 200 words)*

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